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Investigation of the properties of magnetocaloric $Mn_{1-x}Fe_xNiGe$ ($0.05 \le x \le 0.30$) films

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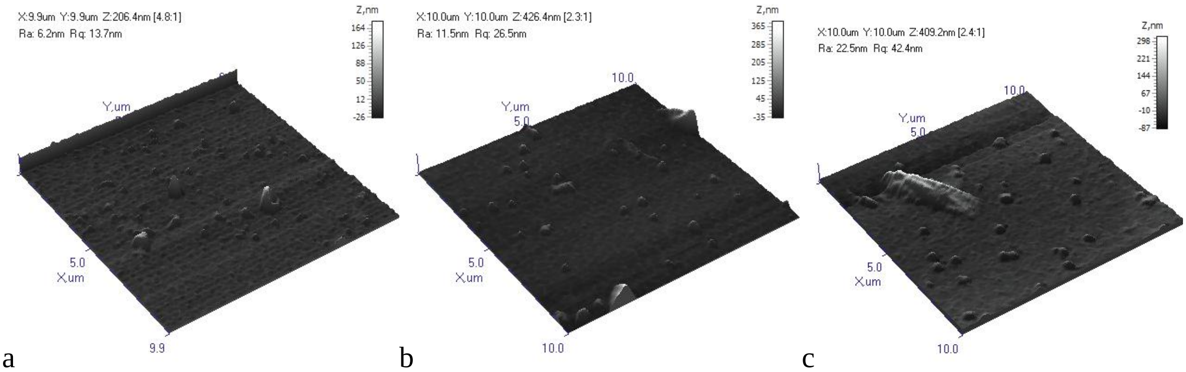
MnNiGe-based solid solutions are currently positioned as "green" magnetocaloric materials, promising for use in magnetic refrigerators [1-3]. The magnetic behavior of the MnNiGe system is strongly dependent on doping, special heat treatment, pressure imposition, etc. One of the most important factors determining the magnetic behavior of the system is the state of the sample – film or massive.

The purpose of the work is to study the microstructure, surface topography and magnetic properties of the samples of solid solutions $Mn_{1-x}Fe_xNiGe$ ($0.05 \le x \le 0.30$) in the state of the film. Polycrystalline samples of solid solutions $Mn_{1-x}Fe_xNiGe$ were synthesized in a single-zone resistance furnace, followed by quenching in water. The resulting alloys were powdered with a grain size about 0.1-0.3 mm. Then using the obtained precursor according to the "flash" method [4], thin films of $Mn_{1-x}Fe_xNiGe$ images were deposited ($0.05 \le x \le 0.30$). The glass slides $18 \times 18 \times 0.5$ mm^3 in sizes were used as substrates. The films were studied by atomic force microscopy (microtest machines NT-206, tips Mikromasch CSC 38) in contact mode. To evaluate the surface, at least 5 scanning sites were selected from different sections of the surface with a size of 20×20 μm^2 and 5×5 μm^2, which allowed averaging the parameters of the relief. The processing of the obtained data was carried out with the help of the program "SurfaceXplorer" according to the technique described in [5].



a b c

Figure 1. The surface topography of the $Mn_{1-x}Fe_xNiGe$ thin film when scanning on a 10×10 μm^2: (a) $x = 0.1$; (b) $x = 0.2$; (c) $x = 0.3$.

AFM studies have shown that the typical surface of thin films of $Mn_{1-x}Fe_xNiGe$, for different values of x, has a similar relief. With a scan area size of 10×10 μm^2 (Fig. 1), uniformly distributed round-shaped structural formations with a size of 0.1-0.3 μm in diameter with an average height of 0.1-0.2 μm are observed on the surface, which can be seen from the section profile (Fig. 2). The distribution of heights for these sites is presented in Figure 2b, there is also an analysis of the orientation of the surface structures 2c, which indicates the presence of a weakly expressed orientation of the formations on the surface. The arithmetic average surface roughness, averaged over 5 different scans, with the specified site selection for $Mn_{0.95}Fe_{0.05}NiGe$ systems is R_a = 8.1 nm, mean square R_q = 11.0. The ratio of the projective surface area to the full one is 0.984. The values for the other combinations of the composition are given in Table 1.

The thickness of the applied coating was estimated by the ratio of the mass of the deposited layer to the density of the substance (X-ray density is used) and surface area of the deposited layer. The results of determining the thickness of the coatings are presented in Table 1.

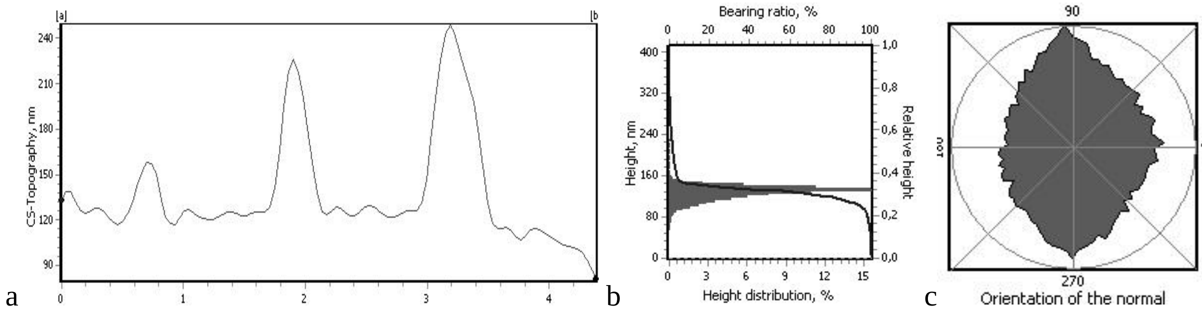


Figure 2. The surface topografy of the $Mn_{0.95}Fe_{0.}$ thin film when scanning on a 10 × 10 μm^2:
(a) cross section; (b) height histogram; (c) orientation of formations on the surface.

Table 1. Parameters of the obtained films.

№	Sample	Thickness, nm	The ratio of the projective surface area to the full	R_a, nm	R_q, nm
1	$Mn_{0.95}Fe_{0.05}NiGe$	705	0.984	8.1	11.0
2	$Mn_{0.90}Fe_{0.10}NiGe$	744	0.987	15.2	29.0
3	$Mn_{0.85}Fe_{0.15}NiGe$	784	0.974	11.5	14.7
4	$Mn_{0.80}Fe_{0.20}NiGe$	868	0.991	9.2	20.4
5	$Mn_{0.75}Fe_{0.25}NiGe$	554	0.992	5.1	13.7
6	$Mn_{0.70}Fe_{0.30}NiGe$	896	0.986	12.1	26.6

Using the AFM images, the multifractal dimension of the surface was calculated using the horizontal section method (area – perimeter). When calculating the fractal dimension, the systematic deviation characteristic of the method of horizontal sections was taken into account [6]. Analysis of the fractality of the studied sites by 500 sublayers gives an average value of the fractal dimension 2.57 the coefficient of self-similarity of 0.785 for 0.75 that change to 3.00 and 0.995 for *x* 0.95, respectively. As can be seen from the table and Fig. 1, as *x* increases, the surface roughness grows, as well as more massive structures are formed on it, more than 1.5 microns in length, 1.5 microns in diameter and from 0.3 to 1 micron in height. In this case, the average value of the fractal dimension of the sites studied increases somewhat in comparison with the main relief and reaches from 2.57 to 3.00, which indicates a developed "bulk" surface.

To determine the phase composition, parameters, and volume of the crystal cell of the samples, X-ray structural studies were performed in Cu Kα radiation at room temperature. We assume the existence of a connection between the magnetic properties of the films and the morphology of their surfaces. At present, the magnetic and magnetocaloric properties of the films are being investigated. The work is in progress.

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